Atom-Based Precision Measurement Physics Postprint

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Abstract

Do the laws of physics vary with time and space? Are fundamental physical constants truly constant? What mechanism leads to the preservation of matter in the universe? To explore these questions, high-energy physics continuously increases energy through accelerators, while astrophysics continuously expands observational scales through telescopes. The laws of the universe should be universal, likely leaving clues in the subtle details of atomic and atom-light interactions that help us answer these questions. Scientists are exploring new physics in nature along multiple paths and in multiple directions. These directions include the cosmic frontier, the high-energy frontier, and the precision measurement frontier belonging to the Chinese Academy of Sciences' Strategic Priority Program on "Atom-based Precision Measurement Physics."

Full Text

Preamble

Strategic Priority Research Program (Category B) of the Chinese Academy of Sciences
ChinaXiv Partner Journal: Precision Measurement Physics Based on Atoms

2 Scientific Problems to be Addressed and Research Foundation

Do the laws of physics vary with time and space? Are fundamental physical constants truly constant? What mechanism preserved matter in the universe? To explore these questions, high-energy physics continuously pushes accelerator energies higher while astrophysics expands observational scales with ever-larger telescopes. Yet the laws of the universe should be universal, likely leaving subtle clues within atoms and their interactions with light that can help answer these fundamental questions. Researchers are exploring new physics along multiple paths and directions, including cosmic frontiers, high-energy frontiers, and the precision measurement frontier represented by the Chinese Academy of Sciences' "Precision Measurement Physics Based on Atoms" Strategic Priority Program.

2.1 Overall Approach and Scientific Tasks

Precision measurement physics based on atoms seeks to discover traces of new physical laws by searching for minute deviations between measured physical quantities and values predicted by existing theoretical frameworks. Historically, such tiny deviations have led to revolutionary discoveries: early observations of discrete atomic spectral series gave birth to quantum mechanics, while discoveries of fine structure and the Lamb shift provided the experimental foundation for relativity, quantum mechanics, and quantum electrodynamics (QED).

The overall research approach of this program is illustrated in Figure 1 [Figure 1: see original paper]. By leveraging frontier techniques such as precision spectroscopy, cold atoms, and matter-wave interferometry, the program conducts tests of fundamental physical laws and measurements of fundamental constants based on atomic systems. It innovates theoretical research in precision measurement physics, explores new concepts and principles, develops novel methods and technologies, and constructs high-stability, ultra-low-noise precision measurement systems. The program also develops high-precision atomic optical clocks to address the need for higher-precision time-frequency standards and reference sources for precision measurements, while building remote time-frequency transfer networks for practical applications. Research on integrating time-frequency transfer with wide-area communications and high-fidelity remote time-frequency comparison aims to solve the challenges of long-distance, high-precision transmission and comparison of time-frequency signals.

Research in atomic-based precision measurement physics enables in-depth investigation of major scientific questions concerning tests of fundamental laws, measurements of physical constants, and frontier exploration of time-frequency metrology. This scrutinizes the limits of applicability of current physical frameworks, discovers new physics and new science, and makes substantive contributions to exploring physics beyond the Standard Model, while expanding China' s international voice in fundamental constant measurement and atomic time-frequency standard formulation.

The program comprises three research projects—testing fundamental physical laws, measuring fundamental physical constants, and frontier exploration of time-frequency metrology—encompassing nine research directions.

In testing fundamental physical laws (Figure 2 [Figure 2: see original paper]): (1) Develop high-precision cold atom interferometry to simultaneously measure gravitational acceleration using two different atomic species (the so-called "atomic Leaning Tower of Pisa" experiment, Figure 3 [Figure 3: see original paper]), testing the weak equivalence principle (universality of free fall for atomic systems) and thus the applicability range of general relativity, while placing more stringent constraints on parameter ranges in new physics models and guiding new theoretical development; (2) Develop laser-controlled two-electron cold atom techniques (Yb, Ra) to test CP symmetry through precision measurement of atomic permanent electric dipole moments (EDM), enhancing understanding of CP violation in fundamental particles and the origin of matter-antimatter asymmetry in the early universe, and exploring new physics at energy scales of 10–100 TeV; (3) Develop dual-linked interferometer correlation detection methods to verify Lorentz invariance at higher precision using optical cavities and explore possible symmetry breaking; (4) Develop laser cooling and trapping techniques for helium and helium-like atoms (ions) and extreme-ultraviolet femtosecond optical frequency comb technology to precisely measure the 1S–2S transition frequencies and fine structure of excited states in He atoms/Li+ ions, enabling high-precision tests of QED in combination with high-precision theoretical calculations.

In measuring fundamental physical constants: (5) Utilize independently developed frequency-locked cavity ring-down spectroscopy combined with precise temperature control at the sub-mK level to measure Doppler broadening of spectral lines and determine the Boltzmann constant k_B to ppm-level precision; (6) Use sympathetic cooling to prepare HD+ molecular ions in their rovibrational ground state and perform high-precision measurements of their rovibrational spectra, comparing experimental results with transition frequency calculations incorporating high-order relativistic and QED effects to determine the proton-to-electron mass ratio mp/me for comparison with CODATA recommended values, thereby testing bound-state QED theory.

In frontier time-frequency exploration: (7) Develop high-precision optical clock systems using trapped ions or optical lattice atoms, precisely controlling effects of motion and external fields on optical frequency transitions, including blackbody radiation and atomic collisions, to achieve 10^{1}-precision atomic optical clocks; test whether fundamental physical constants vary over time through optical frequency comparisons between two different atomic transitions; (8) Solve technical challenges of time-frequency signal attenuation over long distances, distortion during transmission, and incompatibility with wide-area communications, achieving long-distance time-frequency transfer based on fiber-optic communication networks; (9) Theoretically search for highly charged ion (HCI) systems suitable for high-precision atomic clocks, generate HCI using electron beam ion traps (EBIT) and conduct spectroscopic measurements, and explore nuclear optical clock transitions using ion storage ring electron-ion recombination spectroscopy, investigating next-generation optical clocks surpassing 10^{1} precision.

2.2 Research Foundation

The research teams participating in this program have accumulated extensive experience in precision measurement physics and technology over many years. They have constructed the world’ s tallest fountain atom interferometer at 12 meters (Figure 4 [Figure 4: see original paper]), improving the precision of microscopic particle equivalence principle tests from the stagnant level of 10 for over a decade to 10 . The team performed the world’ s first EDM measurement of ^{22} Ra, establishing an upper limit that opens a new pathway for exploring atomic EDM (Figure 5 [Figure 5: see original paper]). They built a helium atomic beam spectroscopy detection apparatus based on laser cooling and single quantum state preparation and detection, obtaining high-precision measurements of the fine-structure splitting (2^3P -2^3P) in He. The team pioneered isotope shift measurements for short-lived neutron-rich nuclei He and He, determining the nuclear charge radii of these exotic nuclei—a representative achievement in using atomic precision spectroscopy to probe nuclear structure that led to an invited review in *Reviews of Modern Physics*. They achieved Li+ trapping and sympathetic cooling with Ca+, performed high-precision calculations of low-lying rovibrational spectra of hydrogen molecular ions at the 10 ^{1} relative precision level, and conducted systematic theoretical work on precision spectroscopy of few-body atomic and molecular systems, including hydrogen molecular ions, antiprotonic helium, and lithium ions. The team proposed a cavity ring-down spectroscopy method for measuring k_B with statistical uncertainty reaching the 10 level. They developed research on trapped and cooled atoms and ions for optical clocks, including Ca+ and Al+ ions and Yb atoms at the Wuhan Institute of Physics and Mathematics, Sr atoms at the National Time Service Center, and Hg atoms at the Shanghai Institute of Optics and Fine Mechanics. They established China’ s first ion optical clock (Figure 6 [Figure 6: see original paper]), measuring the 4S / -3D / optical frequency transition in Ca+ ions with accuracy reaching the 10 ^{1} level—a value adopted as a recommended optical frequency by the International Committee for Time and Frequency. They performed comparisons between two optical clocks, achieving stability and uncertainty at the 10 ^{1} level, and proposed an all-optical trapped-ion optical clock scheme. The team conducted research on high-precision time-frequency transfer via optical fiber, achieving time-interval measurement precision at internationally advanced levels, realizing simultaneous transmission of time and frequency signals over optical fiber for application in China’ s satellite navigation system, and demonstrating optical frequency signal transfer over 120 km of field fiber with a stability better than 6×10 ^{1} at ten thousand seconds using independently developed ultra-narrow-linewidth fiber lasers. On the theoretical front, team members first proposed the concept of novel clocks based on HCI, highlighting their advantages and development potential, while their proposal for Yb atomic optical lattice clocks has been implemented in laboratories worldwide. The team has also made highly influential contributions to parity violation physics in atomic systems.

The program is hosted by the Wuhan Institute of Physics and Mathematics, Chinese Academy of Sciences, with participating units including the University of Science and Technology of China, National Time Service Center, Shanghai Institute of Optics and Fine Mechanics, Institute of Physics, Institute of Theoretical Physics, Institute of Modern Physics, and Anhui Institute of Optics and Fine Mechanics. Team members come from the State Key Laboratory of Magnetic Resonance and Atomic and Molecular Physics, the Hefei National Laboratory for Physical Sciences at the Microscale (under construction), and the Lanzhou Heavy Ion Accelerator National Laboratory, as well as three CAS Key Laboratories of Atomic Frequency Standards, Quantum Optics, and Time-Frequency Metrology, providing an integrated platform advantage for precision measurement physics research.

In terms of connection with national platforms under construction, the "Precision Gravity Measurement Research Facility" (PGMF), a major national scientific infrastructure being built by the Wuhan Institute of Physics and Mathematics in collaboration with Huazhong University of Science and Technology and other units, has passed feasibility review and will be completed within five years. PGMF will provide precise gravity references and calibration of gravitational environments for this program. China will gradually construct a space station starting in 2018, equipped with a "Space Station High-Precision Time-Frequency System"experimental platform that includes space-based atomic clock systems and space-ground time-frequency transfer links. Recently, a space cold atom clock developed by the Shanghai Institute of Optics and Fine Mechanics was launched aboard Tiangong-2, laying the foundation for conducting precision physics experiments in space. Supported by the National Development and Reform Commission, the University of Science and Technology of China is constructing the "Beijing-Shanghai" quantum secure communication backbone connecting Beijing, Shanghai, Jinan, and Hefei, with a second-phase "Beijing-Wuhan-Guangzhou" trunk line under planning. The National Time Service Center is responsible for generating, maintaining, and broadcasting China' s standard time and frequency, participates in International Atomic Time calculations, and operates major national scientific infrastructure including long-wave and short-wave time service systems and a communication satellite-based regional navigation and positioning test system.

3 Expected Results and Impact

Through implementation of this program, we anticipate testing the applicability of known physics and exploring new physics at unprecedented precision—either discovering new physics or placing more stringent constraints on parameters in various new physics models. The program will enhance understanding of CP violation in fundamental particles and the origin of matter-antimatter asymmetry in the early universe, determine the Boltzmann constant k_B to the ppm level through spectroscopic methods with results contributing to new definitions of the Boltzmann constant and the kelvin temperature unit, and achieve precision measurements of physical constants such as mp/me with data incorporated into CODATA. Atomic optical frequency measurements will enter international recommended values, expanding China’ s international voice in time-frequency standard formulation. The program will establish a world-leading remote time-frequency transfer network integrated with quantum communication networks, promoting applications of optical clocks and atom interferometers in fundamental physics and other high-precision scientific fields.

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Note: Figure translations are in progress. See original paper for figures.